APPENDIX A

QUESTIONNAIRE

Contact Name: SR-71 Blackbird

Collaborators:

Name:

Organization:

Name:

Organization:

Please provide information about the analyses completed:

1. Analysis Software (name and version)
    a. FEA software (if applicable): StressCheck, ESRD, Inc.
    b. Crack growth software: Crack Growth Analysis Tool (CPAT), a non COTS simulation application developed by ESRD, Inc.
2. FEA Model Setup (if applicable)
    a. Describe the boundary conditions utilized in the FEMs, to include applied loads and constraints

    Boundary conditions—symmetry in loads and geometry cut the whole coupon domain into half for the simulation domain. Net Section (gage) plane had flat crack face and had symmetry constraints everywhere except crack face.

    The interference fit is modeled with two distinct inputs: distributed normal springs on the hole, and imposed radial displacements on the springs.

    The wide or grip end of coupon is constrained to simulate test machine grip constraint. The wide end is loaded with constant stress. The out of plane (z) displacement is constrained on the wide end. Two faces on grip end are constrained with normal displacements zero.

    b. Describe the methods to define and control the crack front shape and control meshing along the crack front

Input is the two parameters defining an elliptic curve that is initial crack front. From 9 to 21 spline points were used to define crack front. Case # 1 used 21 points throughout. Case #2 used 21 points from steps 0 to 205, 16 points steps 206-208, and 12 points step 209 to 276 (end).

Case #3 used 21 points from steps 0 to 76 , 12 points step 77, 9 points step 78 to 80, 12 points steps 81 to 136, and 18 points steps 137 to 139 (end).

StressCheck automesh option “Boundary Layer” used to create more elements in the mesh along crack front.

Crack propagation was iterative. At each step,

a) geometry created (crack edge is a spline),
b) far field end of coupon loaded,
c) boundary conditions applied,
d) FEA solution is computed: First the linear solution is computed, then the nonlinear solution is computed. The nonlinear solution is required to account for springs in incomplete contact on the hole surface under load; this is sometimes referred to as “hole propping.”
e) Stress Intensity Factors (SIFs), are computed
f) CPAT computes crack growth rates at each spline point,
g) a decision was made how far to extend the crack (user input percentage of crack dimension),
h) the number of cycles in the step is computed for that crack increment, all spline points are moved based on the crack growth rates at the spline points in the direction normal to the spline at the spline points, and
i) at the end of the step a new crack and new StressCheck model created and the process starts again for new step from b) to i).
j) Steps b) to i) are repeated until ‘failure.’ Several reasons for failure: analyst stops before completion, crack runs out to a free edge away from the hole, or FEA software has trouble grabbing the crack front so that the SIFs can be computed. Often the last one can be worked around by backing up computations to an earlier step, and starting again with different crack increment or different number of spline points defining the crack front. SIFs that exceeded fracture toughness were flagged (that is, they were “warnings”) but did not stop the computations (that is, they were not “errors”).

3. Interference Fit Modeling
    a. Describe the methods used to characterize and incorporate the effect of the IFF. Conceptually the interference fit pins affect crack growth in two ways: 1) by changing (usually increasing) the SIFs at the maximum load, and 2) by increasing the effective stress ratios at the crack front.
    As stated before, to simulate the pin in the hole, normal nonlinear springs are distributed around the hole. Nonlinear iterations are needed to define the area on the hole that is contact with the spring, aka ‘hole propping.’

b. If the fastener effect was derived from a closed form solution, what were the assumptions of the solutions? Is the solution based on empirical data or FEM correlations?
N/A

c. If the fastener was modeled using FEA, does the model consider non-linear effects? Was multi-body contact used? If contact was used, what friction related assumptions were made?
Fasteners/pins were modeled with normal nonlinear springs distributed around the hole. The spring constant was defined to simulate the bearing stiffness of the pin. Nonlinear iterations are needed to define the regions of contact between the springs and the hole. Friction was not simulated.

4. Stress Intensity Factor Calculations
   a. Describe the methods used to extract and calculate the stress intensity factors for applied remote loads
   SIFs are computed directly from the FE solution. A contour integral method is used to compute the SIFs.
   b. Describe the methods used to incorporate the stress intensity factors into the crack growth code (superposition, etc.)

   Simulations assume that only two parameters are needed to control crack growth, maximum SIFs and stress ratios. SIFs and stress ratios are computed at every single spline point, and crack growth rates computed separately at each spline point.

$$\Delta K_I = K_{max} - K_{min}$$

$$R = \frac{K_{min}}{K_{max}}$$

   Since nonlinear iterations are needed to adequately define the area of pin (as simulated with the normal springs) in contact with the hole, and that area depends on several parameters: applied load, hole diameter, and the amount of interference in the pin, the nonlinear iteration must be completed at the maximum AND minimum applied loads. K_{max} is computed after nonlinear iterations at the maximum applied load; K_{min} is computed after nonlinear iterations at the minimum applied load.

5. Crack Growth Predictions

a. Describe the material model approach used for the crack growth predictions (NASGRO, tabular, etc.) and the assumptions/approach used for “threshold”, stress ratio (R) shift, and negative R behavior.
   The crack growth rates provided for this challenged were used without modification.
b. What growth increment was utilized between stress intensity calculations?
   Most of the time, 5% growth increment was used. In some steps, that was varied down to 1%. In some testing we have done in the past, there is very little difference in the results if 1% or 5% is used, though there is a huge difference in the amount of CPU (simulation) time required.

6. Provide any additional details that may be pertinent to the analyses completed

When extracting the computed data we have provided, please remember these two things: 1) the first point is defined as the “c” crack length along the bottom surface, and 2) while we tried to use the same number of points to define the crack front (21 points) through all simulations, we encountered some numerical difficulties that required us to vary the number of points in the simulations of the two IFF conditions, 2 and 3.